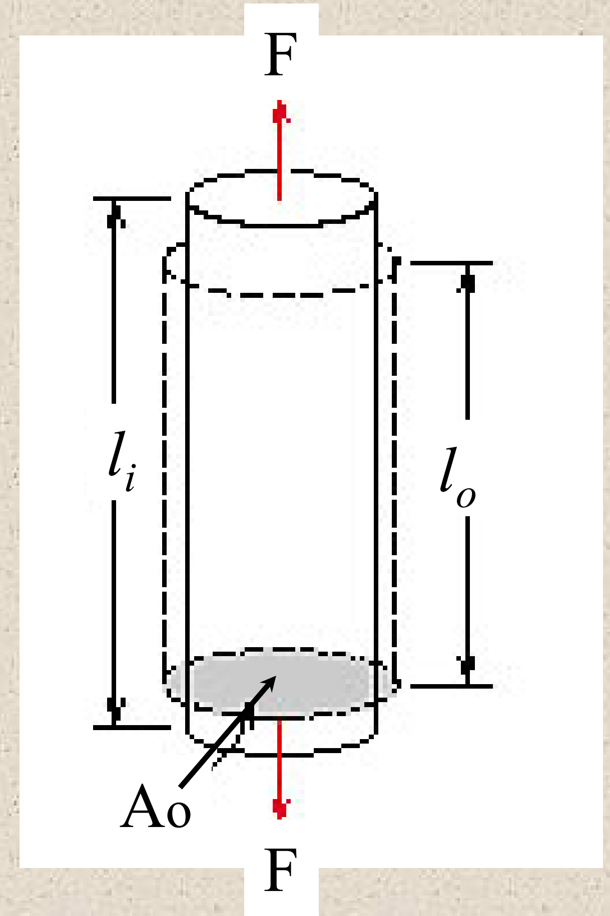
- *Tensile Test*
- *Hardness*
- *Fracture*
  - *Charpy Impact Test*
  - *Fracture Mechanics and K_{IC}*
- *Fatigue*
- *Creep*

Definition of Stress and Strain

Dotted line - initial state



Tension/Compression

<u>Engineering stress (σ):</u>

$\sigma = F/A_o$

Units?

<u>Engineering strain (ε):</u>

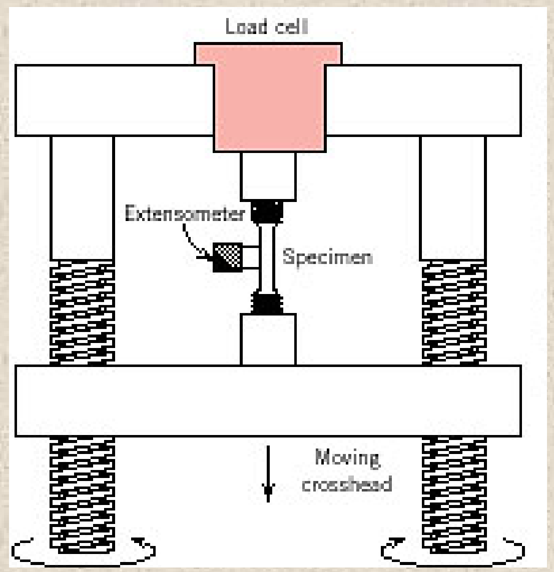
$\varepsilon = l_i - l_o / l_o = \Delta l / l_o$

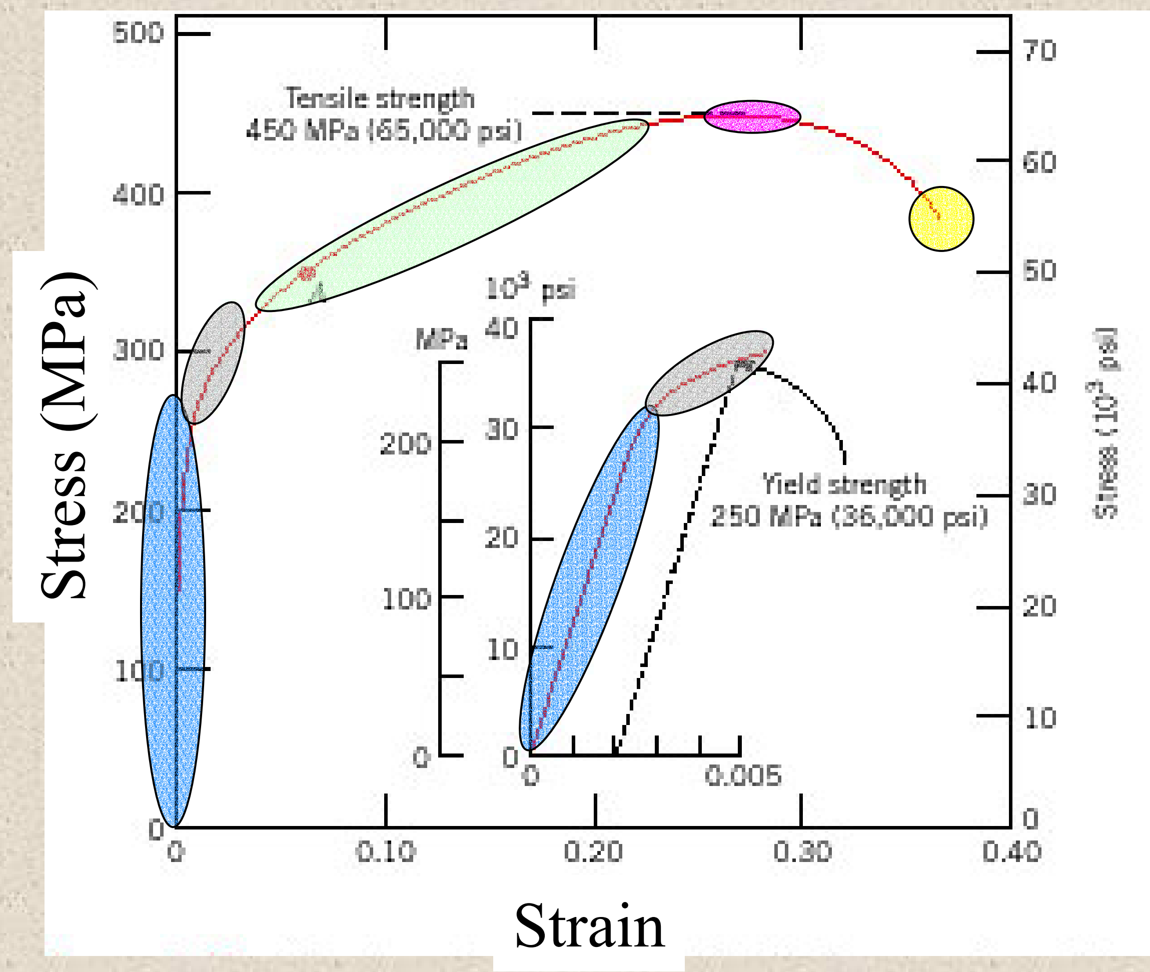
Units?

$\varepsilon \Rightarrow \Rightarrow$ deformation

The Tensile Test

The Tensile Test





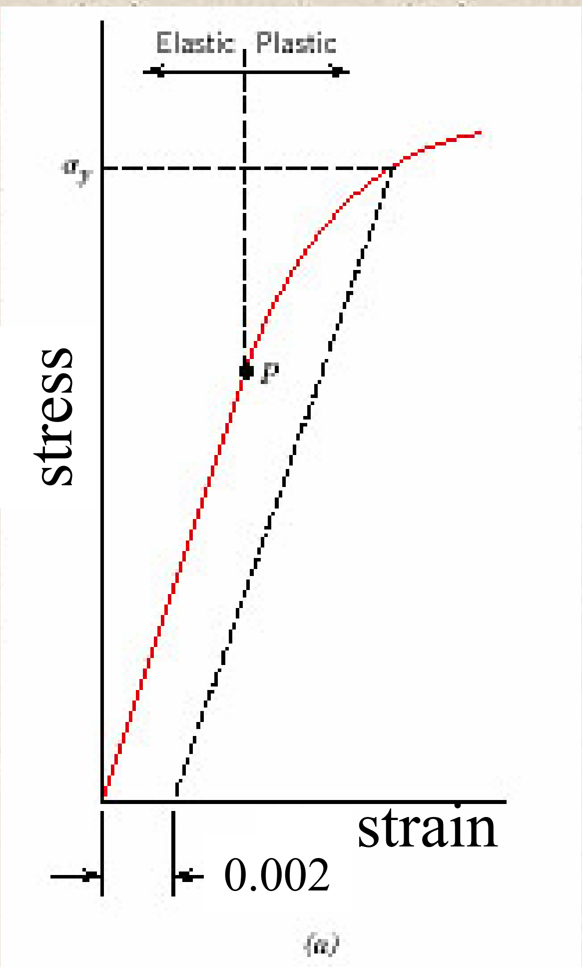
The tensile test - elastic deformation

- ε is <u>not permanent</u> in elastic regime
- <u>Hooke's Law</u>: $\sigma = E\varepsilon$

  E $\Rightarrow$ <u>Young's modulus/modulus of elasticity</u>

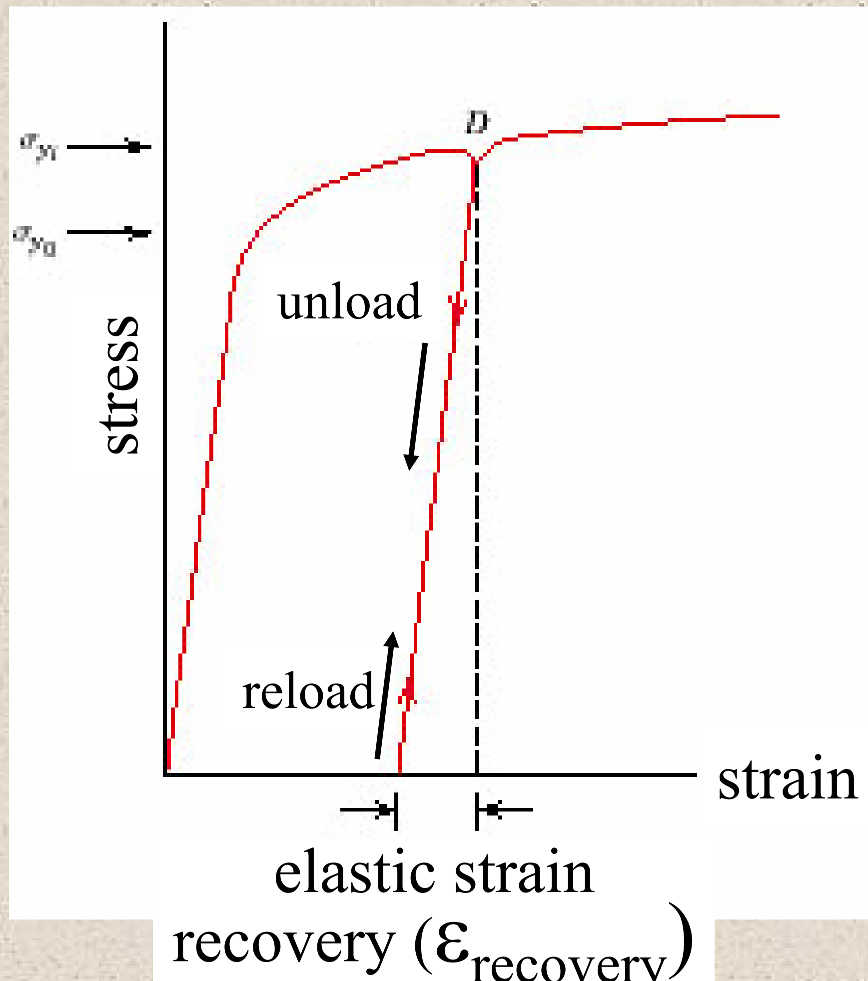
  Units?
- E ranges from 13-400 GPa in metals
- <u>Poisson's ration</u> (μ) = the ratio of lateral strain (x) to axial strain (z) = $-\varepsilon_x / \varepsilon_z$

The tensile test - plastic deformation and yielding



- ε_p is permanent in plastic regime
- Typically not a distinct proportional limit or yield point (P)
- Yield strength (σ_y) is determined at an offset of 0.002 strain
- For most metals, deformation is plastic after $\varepsilon = 0.005$
- σ_y varies from 35-1400 MPa in metals

The tensile test – <u>work-hardening</u> or <u>strain hardening</u>

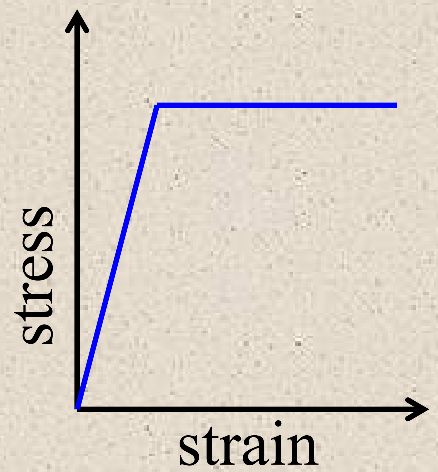


- Recall elastic strain (ε_e) is not permanent

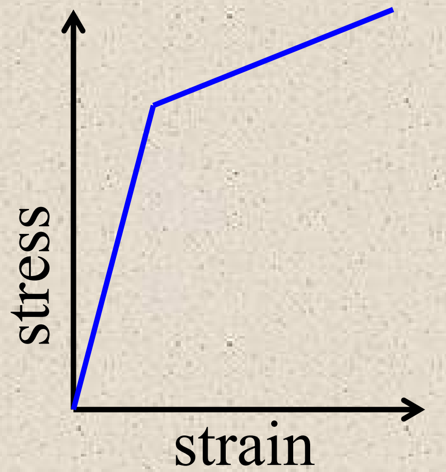
- $\varepsilon_{total} = \varepsilon_e + \varepsilon_p$
- $\varepsilon_e = \varepsilon_{recovery} = \sigma_{yi}/E$

The tensile test – work-hardening

- Defined: after yielding, a continually larger stress is required to continue yielding (a.k.a., strain-hardening)
- Estimations:



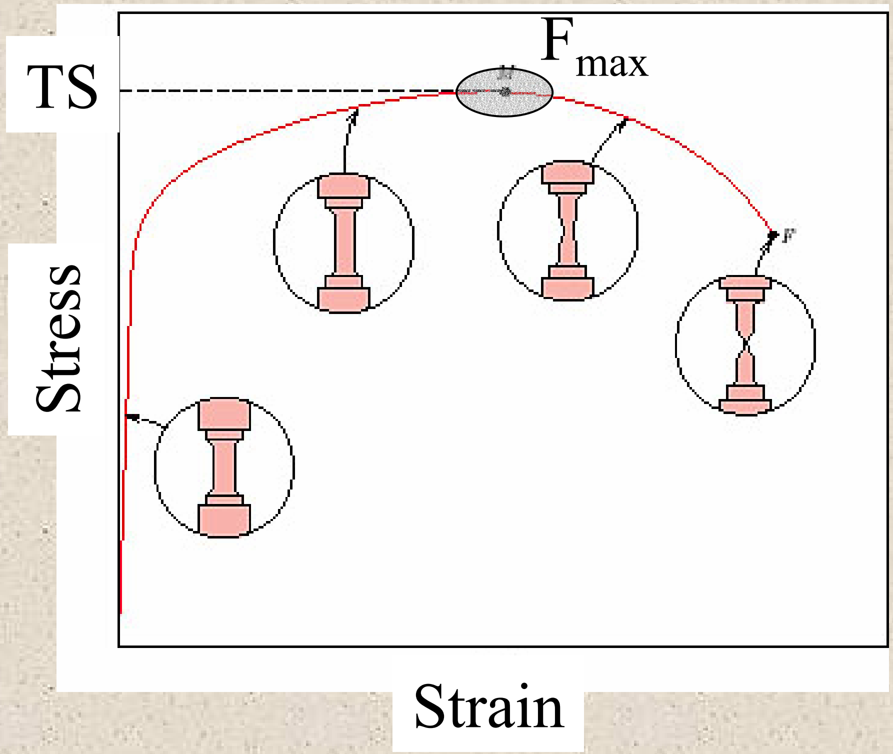
elastic-perfectly plastic (no work-hardening – used in Design!)



linear work-hardening

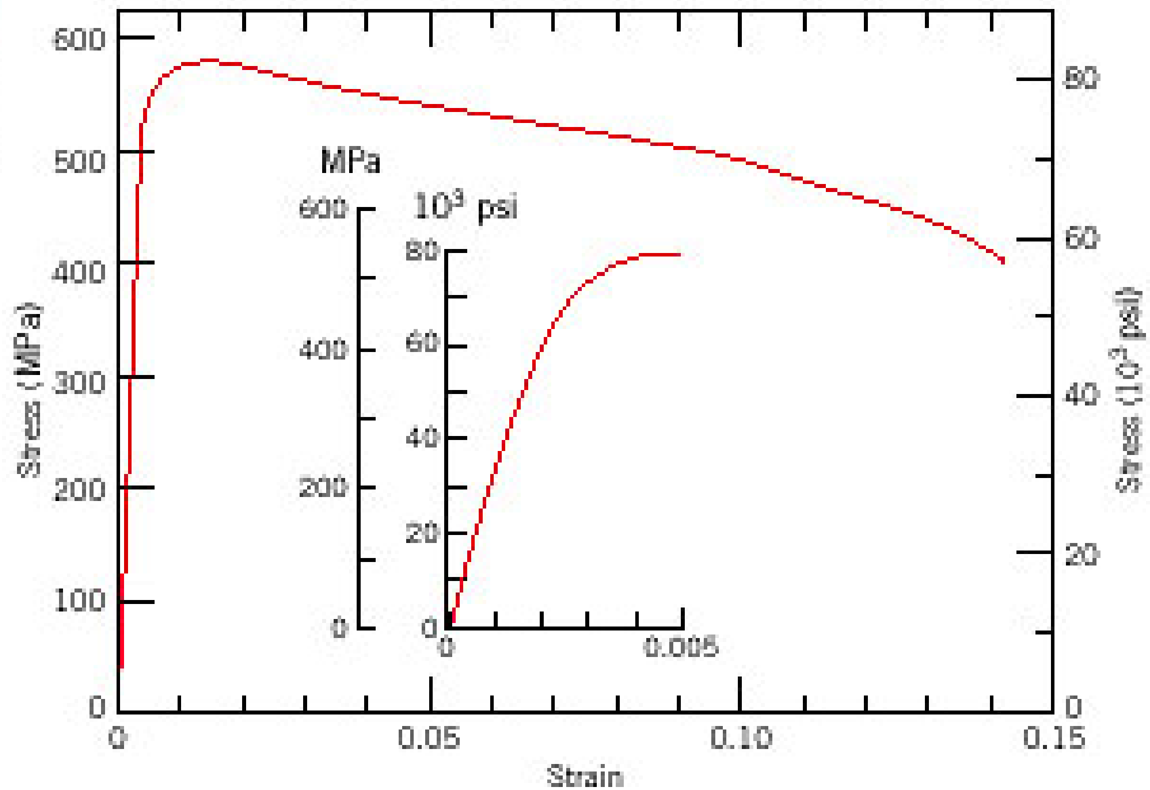
The tensile test - tensile strength

- Tensile strength (TS), or ultimate strength (σ_{ult}) = F_{max}/A_o
- Point of tensile instability or necking
- After this point, strain is not uniform.
- Ranges from 50-3000 MPa in metals



Consider a cylindrical specimen of a steel alloy 10 mm in diameter and 75 mm long that is pulled in tension (see figure below). Determine the elongation when a load of 23,500 N is applied.

Figure 6.21 Tensile stress–strain behavior for a plain carbon steel.



The tensile test – ductility

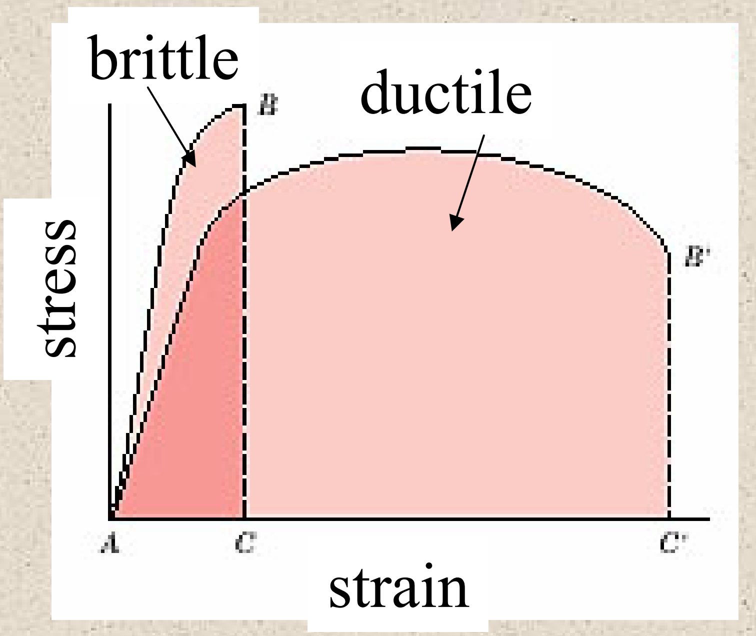
- Ductility $\Rightarrow$ measure of the degree of plastic (permanent) deformation before fracture
- Strain at failure

ε_f (%)= 100 $(l_f - l_o)/l_o$

- Percent reduction in area

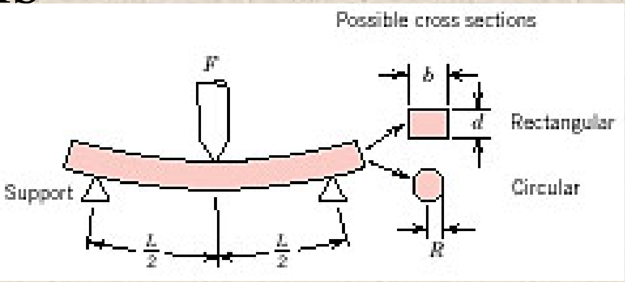
%RA = 100 $(A_o - A_f)/A_o$

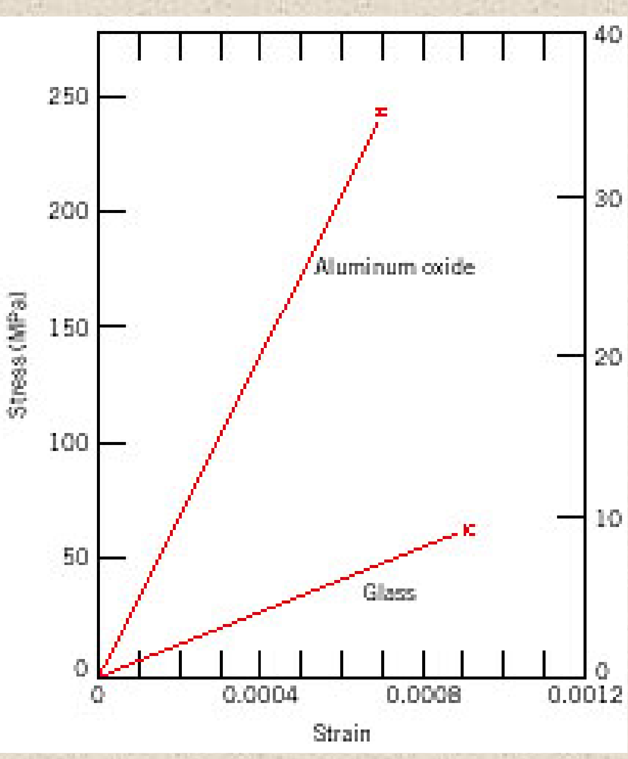
- Ductility is also related to area under stress-strain curve



Measurement of elastic properties for brittle materials

- Flex tests are used to determine E for brittle materials
- Why can't we do tensile tests on brittle materials?





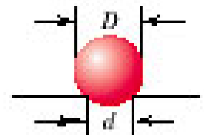
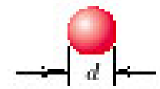
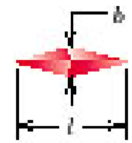
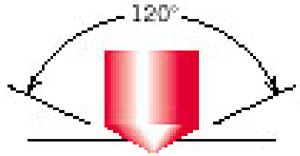
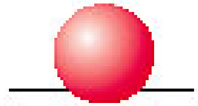
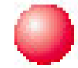
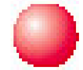
Hardness

Hardness

- Non-destructive measure of strength
- Size of indent under controlled loading
- Various hardness scales
  - Rockwell B
  - Rockwell C
  - Vickers
- Must make sure you are using the correct load and indenter geometry for the scale of interest.

Hardness

Table 6.4 Hardness Testing Techniques

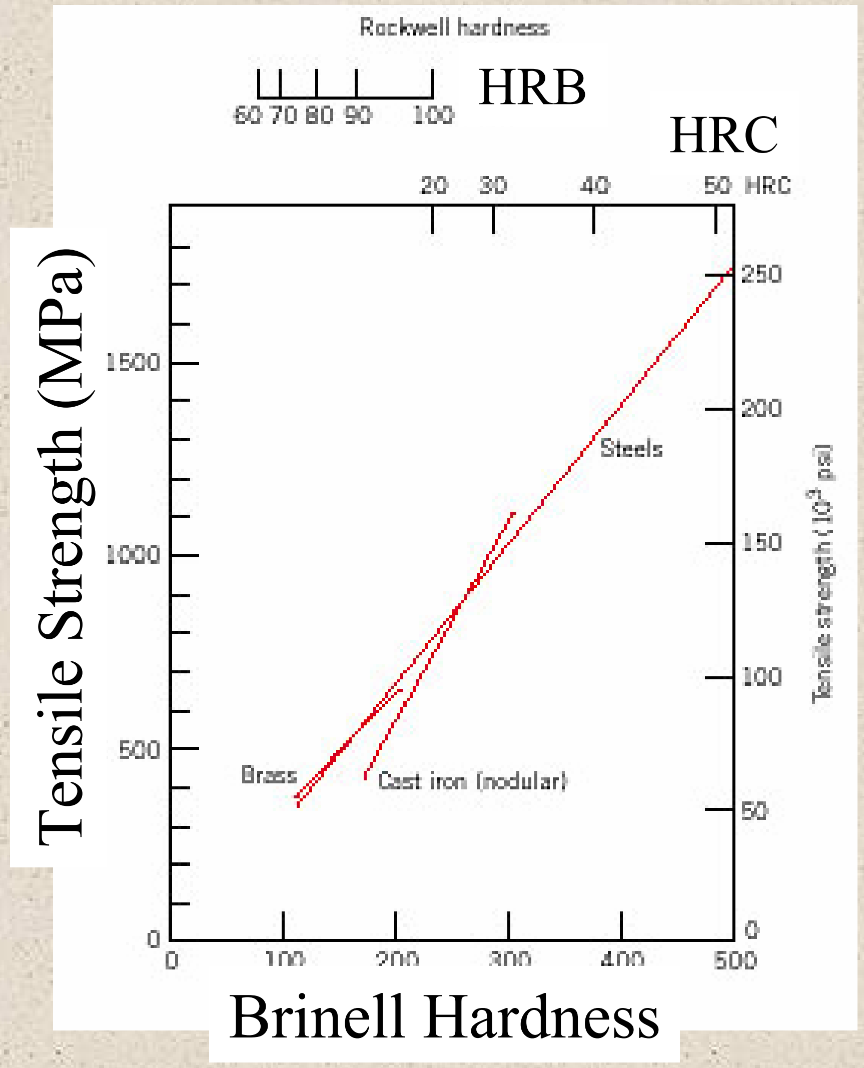
Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in. diameter steel spheres	 	 	60 kg, 100 kg, 150 kg: Rockwell 15 kg, 30 kg, 45 kg: Superficial Rockwell	

[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

Source: Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

Hardness

- Conversions listed in ASTM E140 (mostly steels)
- Also correlations between hardness and tensile strength (mostly steels)
- Can develop the correlation for any material



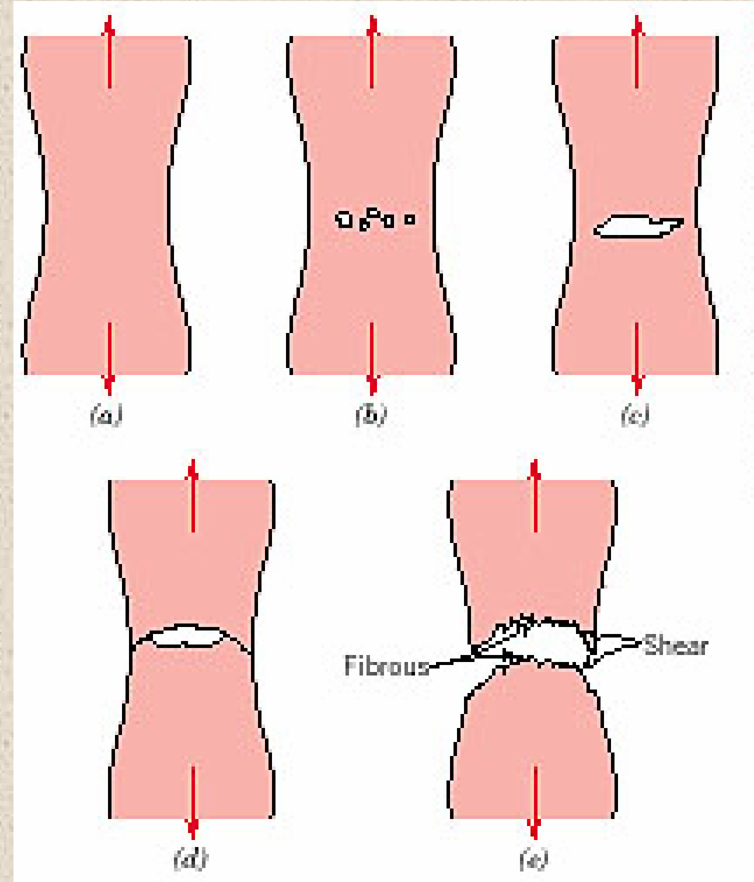
Fracture

Fracture

- Fracture is the separation of material below the melting point.
- Fracture involves crack initiation + crack propagation
- Ductile fracture – a large amount of plastic deformation occurs prior to fracture
- Brittle fracture – little or no plastic deformation occurs prior to fracture
- “Ductile and brittle” are relative terms

Ductile fracture

- Also called "stable fracture" or "tearing".
- A ductile crack resists further extension without an increase in stress
- Example of a typical cup and cone fracture in a tensile test—
- Edges are called shear lips and are 45^{o} to applied stress



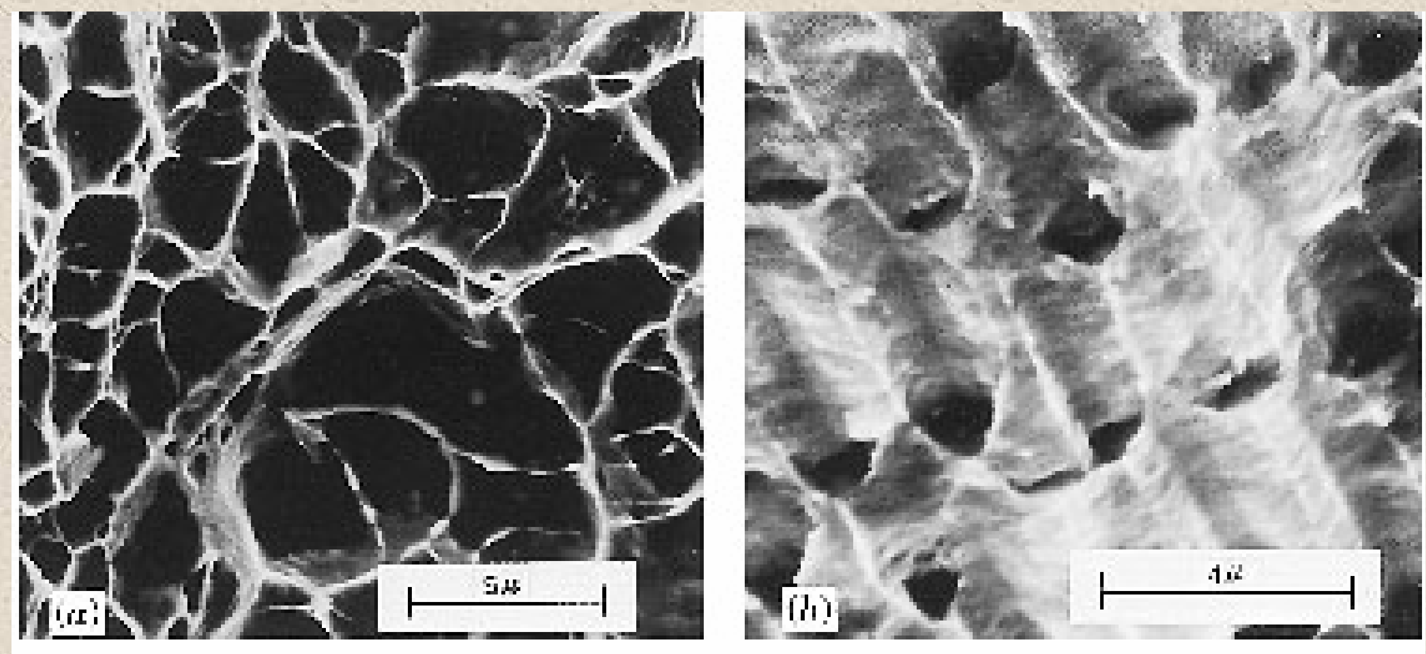
Ductile fracture


(a)

Cup and cone fracture in Al
macroscopic appearance

Ductile fracture

Microscopic appearance (SEM)

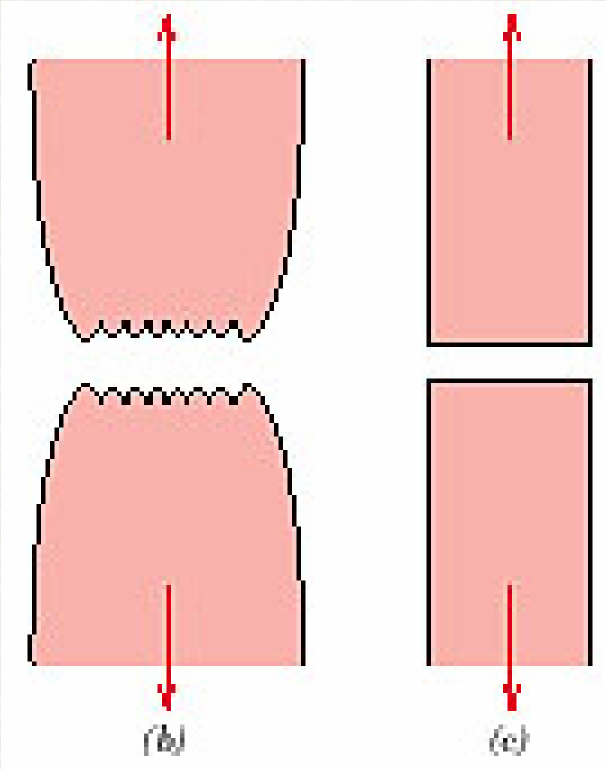


Equaixed microvoids or dimples in center

Elongated microvoids in shear lip

Brittle fracture

- Also called "unstable cracking" or "fast fracture".
- A brittle crack does not require additional stress to extend.
- Very little deformation (%RA) accompanies fracture.
- Crack propagation is perpendicular to stress.

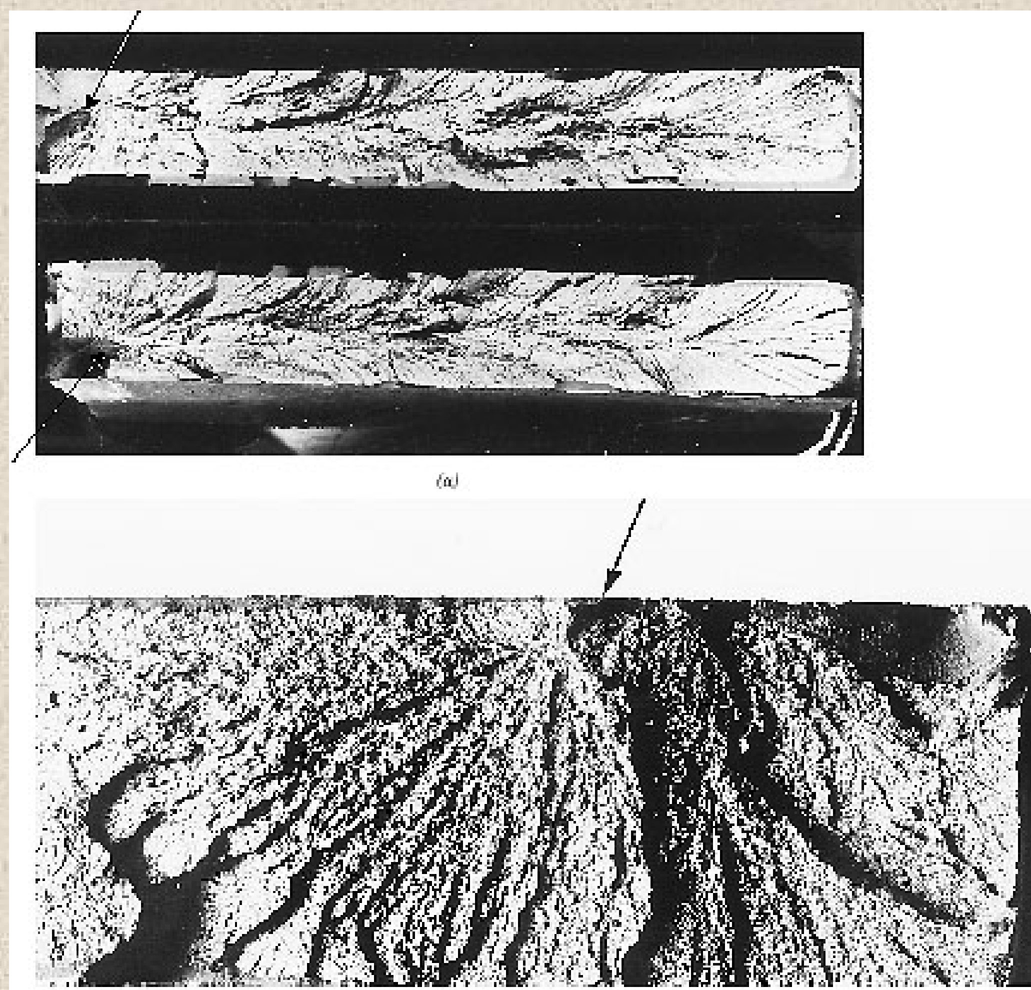


ductile cup-and-cone brittle fracture

Brittle fracture

Brittle fracture appearance in a mild steel tensile specimen

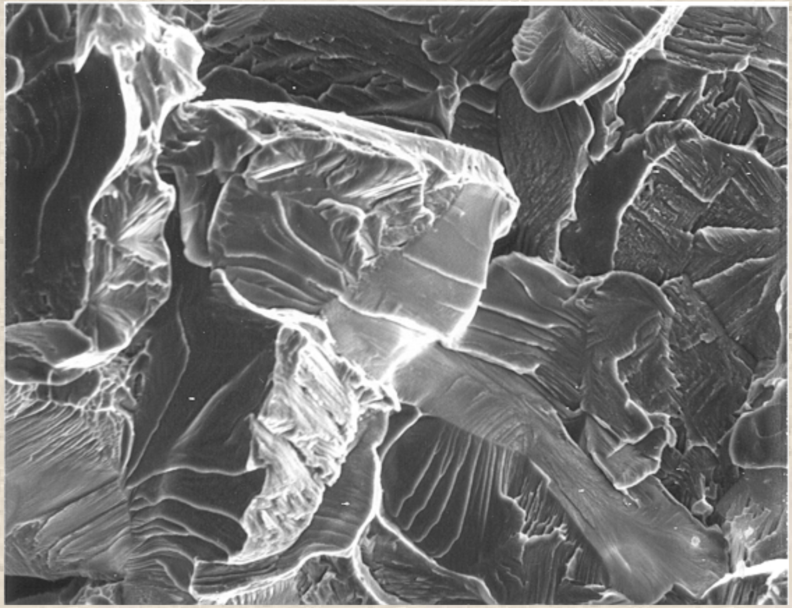
Brittle fracture



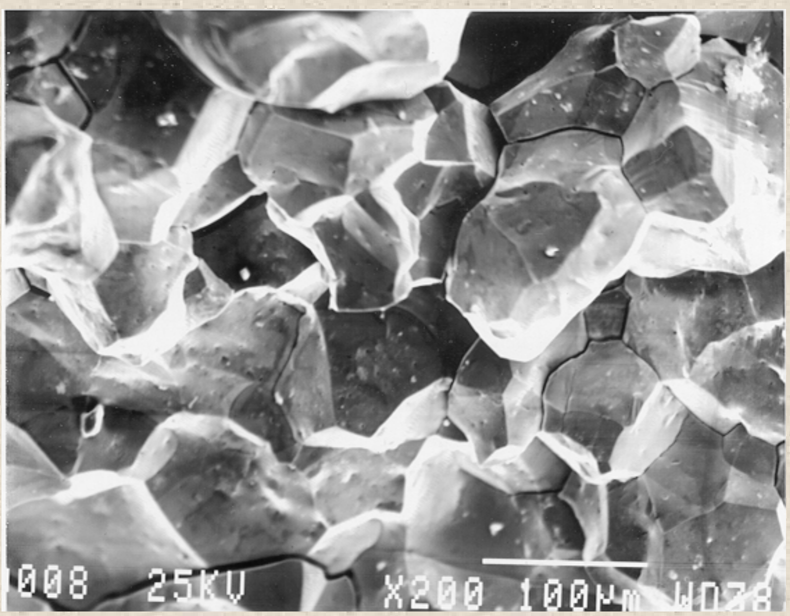
- Chevron markings or "river markings" are indicative of brittle fracture and can be traced back to crack origin.

Brittle fracture-microscopic appearance (SEM)

(1) transgranular (TG) -
fracture path across grains, also called cleavage



(2) intergranular (IG) -
fracture path follows grain boundaries



Toughness

Toughness is a measure of a materials' ability to resist fracture.

How do we measure toughness?

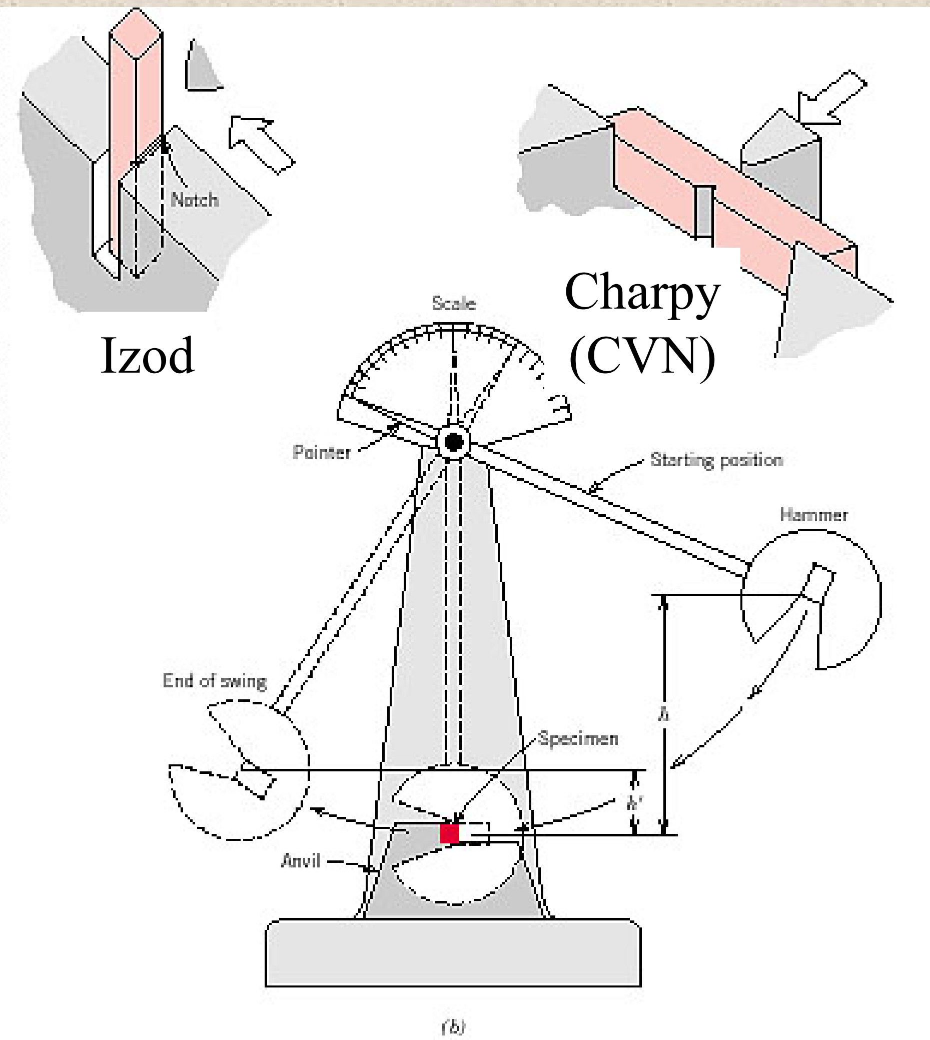
- Smooth specimen (tensile test)
  - toughness (T)=area under σ-ε curve (J/m^3 or Pa)
- Notch toughness (impact test)
  - toughness under a *dynamic load and stress concentration (notch)*
- Fracture toughness
  - toughness in the presence of a *pre-existing crack*

Impact test

- Simple, inexpensive test created to evaluate material toughness under more severe conditions than a tensile test
  - ?
  - ?
  - ?
- Measure energy absorbed during impact and fracture (= impact energy or notch toughness).

How?

Impact test

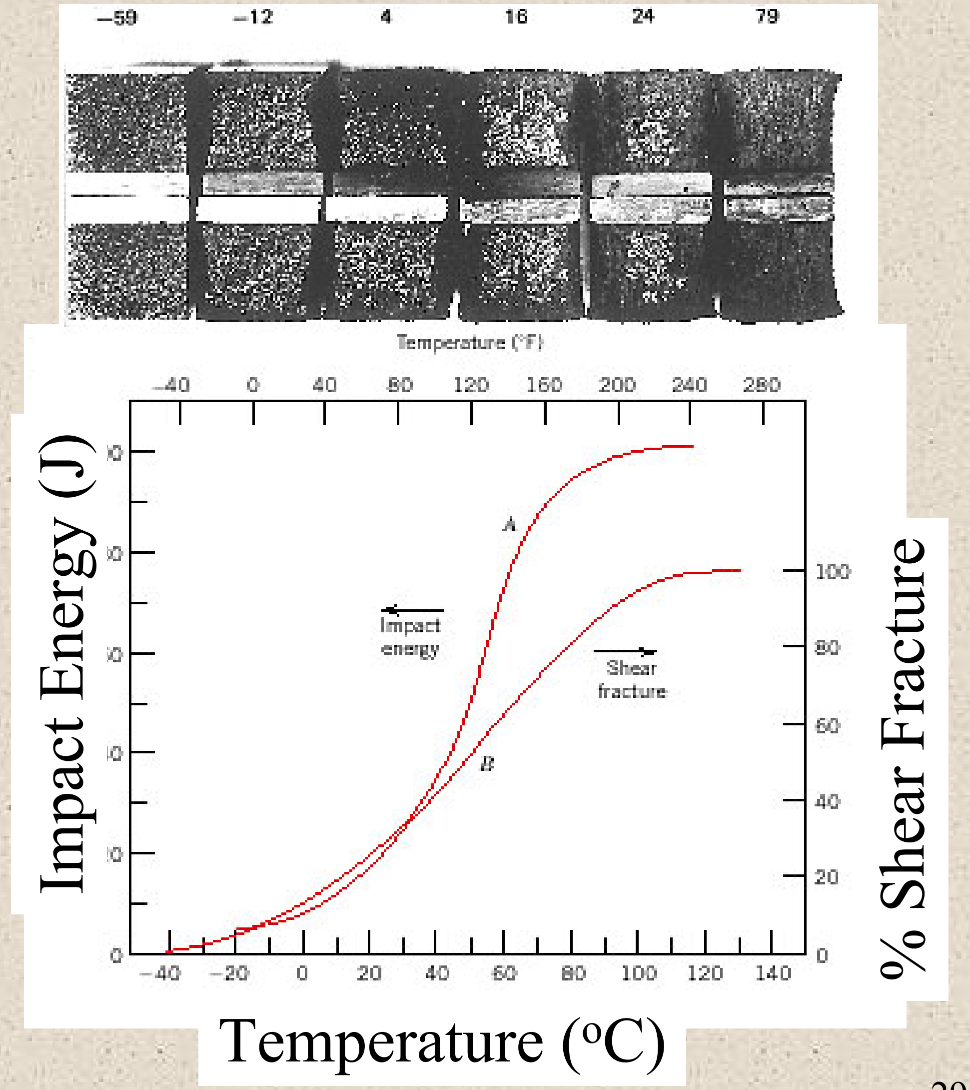


- Two standard types, CVN most common.
- Absorbed energy determined by height of pendulum after impact.
- Fracture surfaces are also evaluated.
- Impact energy is dependent on geometry of specimen.
- Impact energy is a <u>qualitative measure</u> and is not used for design purposes.

Impact test - BCC ductile-to-brittle transition

- BCC materials typically transition from ductile to brittle behavior with *decreasing temperature* or *increasing strain rate*

- DBTT



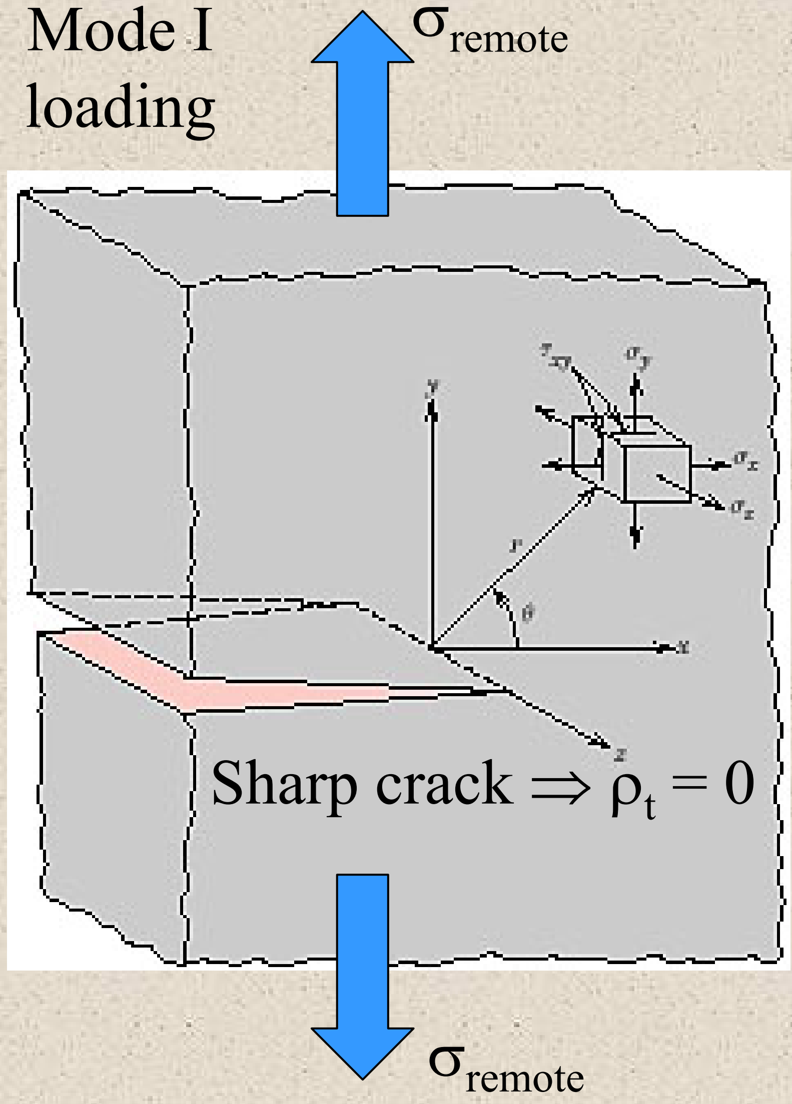
Fracture Mechanics

Basic assumption: There will always exist crack-like defects in a material

Fracture mechanics is used to evaluate the defect tolerance of a structure and measure toughness in the presence of a *pre-existing crack*

Fracture Mechanics

Mode I loading



Applied stress intensity factor (K) is given by:

$$K\ (MPa\sqrt{m}) = f\,\sigma_{remote}\sqrt{\pi a}$$

a = crack depth

f is a function of a, geometry and loading mode.

Fracture occurs when K reaches a critical value called the fracture toughness (K_{Ic})

Fracture Mechanics

Table 8.1 Room-Temperature Yield Strength and Plane Strain Fracture Toughness Data for Selected Engineering Materials

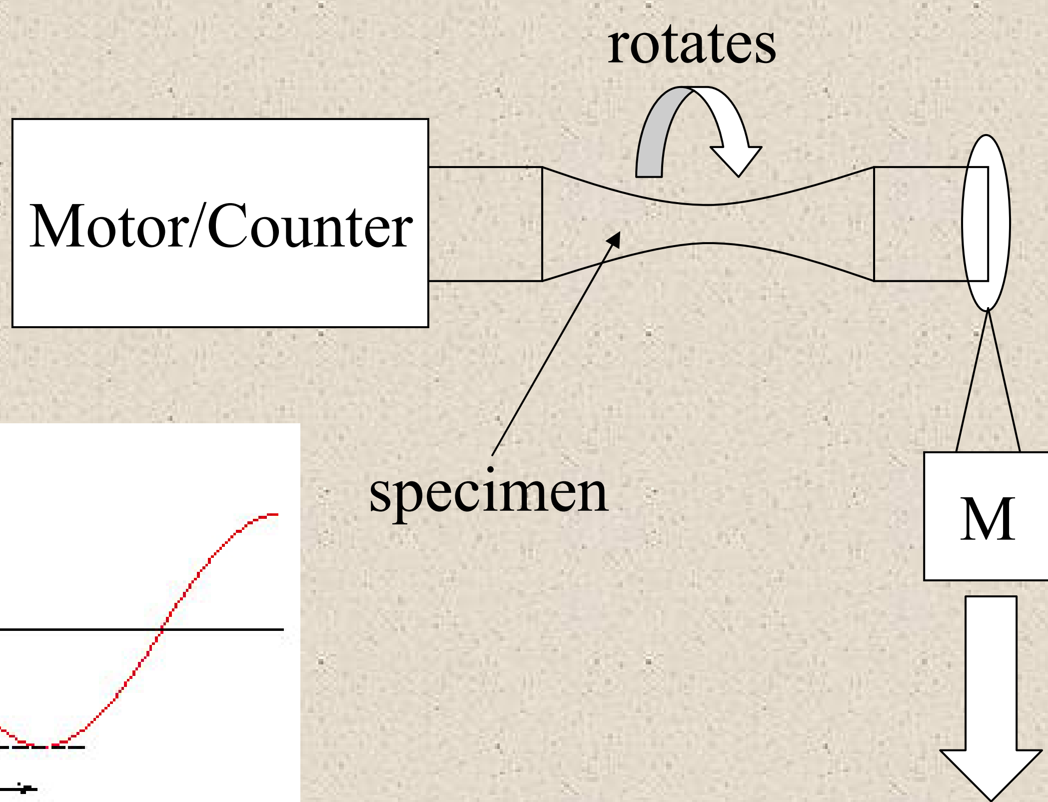
	Yield Strength		K_{Ic}	
Material	*MPa*	*ksi*	$MPa\sqrt{m}$	$ksi\sqrt{in.}$
Metals				
Aluminum Alloy[a] (7075-T651)	495	72	24	22
Aluminum Alloy[a] (2024-T3)	345	50	44	40
Titanium Alloy[a] (Ti-6Al-4V)	910	132	55	50
Alloy Steel[a] (4340 tempered @ 260°C)	1640	238	50.0	45.8
Alloy Steel[a] (4340 tempered @ 425°C)	1420	206	87.4	80.0
Ceramics				
Concrete	—	—	0.2–1.4	0.18–1.27
Soda-Lime Glass	—	—	0.7–0.8	0.64–0.73
Aluminum Oxide	—	—	2.7–5.0	2.5–4.6

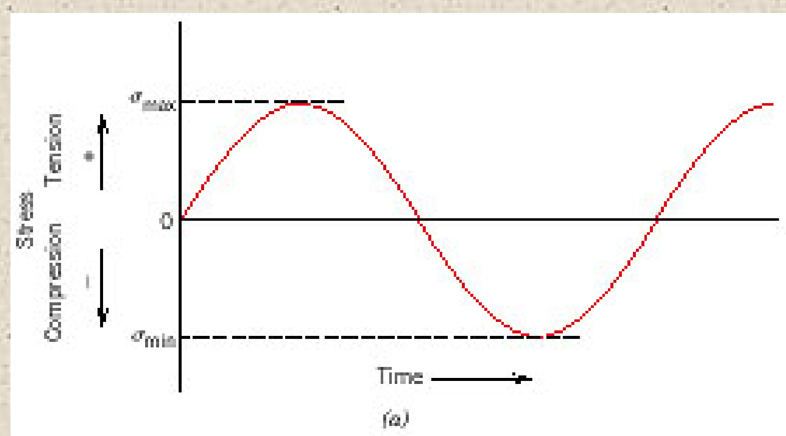
Fatigue

Fatigue

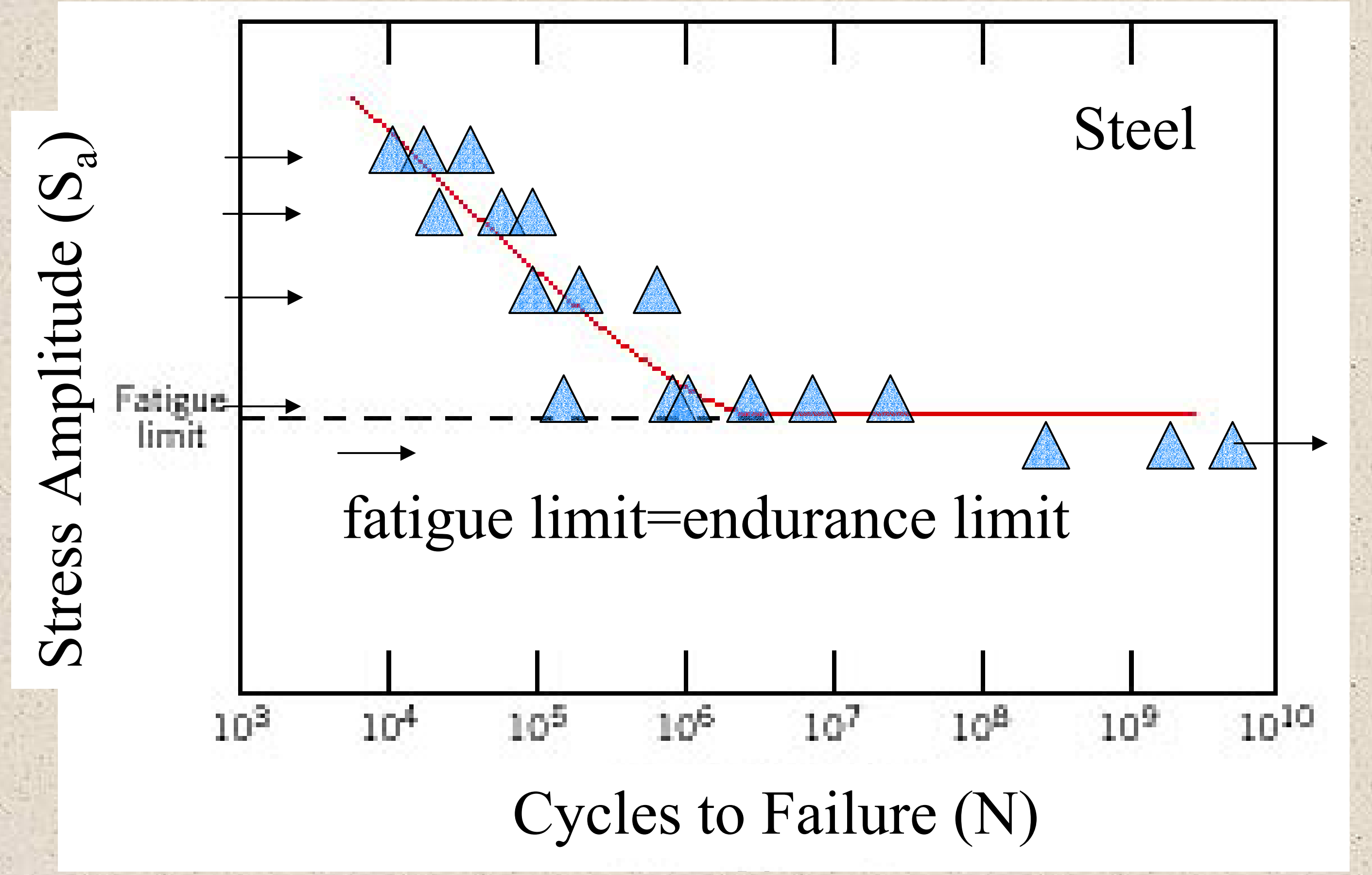
- Fatigue- damage process that occurs as a result of fluctuating stresses.
- Failures occur at remote stress levels below the σ_y or UTS associated with a static load.
- Fatigue is macroscopically brittle in nature, i.e., there is only a small amount of plastic deformation associated with the process.
- Occurs in both ductile and brittle materials.
- Responsible for ~90% of metallic failures.

Rotating bending fatigue test





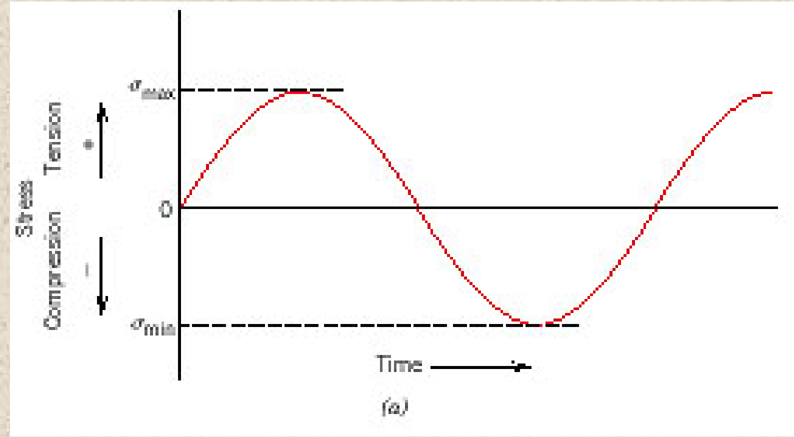
Fatigue Initiation Data: The S-N Curve

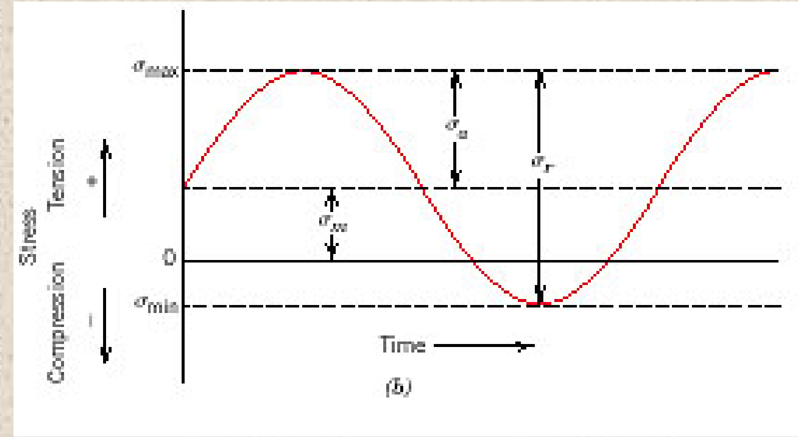


Al and Cu do not show a fatigue limit, i.e. fatigue failure will occur at any stress level if you wait long enough.

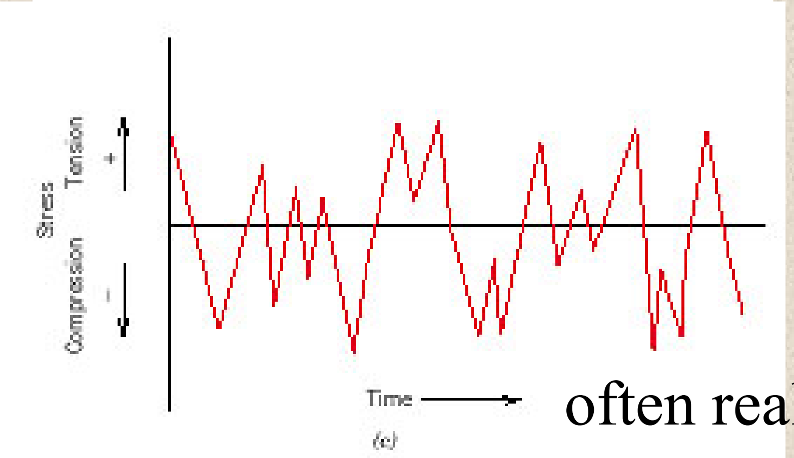
Fatigue "spectra"

fully reversed ($\sigma_{mean} = 0$) pre-loaded ($\sigma_{mean} \neq 0$)





frequency (ω) =cycles/time



often real life

Factors that affect fatigue life and shift the S-N curve

- Mean stress $\Uparrow$, $N_f \Downarrow$
- Surface effects

  scratches: $\Downarrow N_f$ by introducing stress raisers

  case-hardening: $\Uparrow N_f$ by increasing strength of surface

  shot peening: $\Uparrow N_f$ by introducing compressive stresses
- Environment

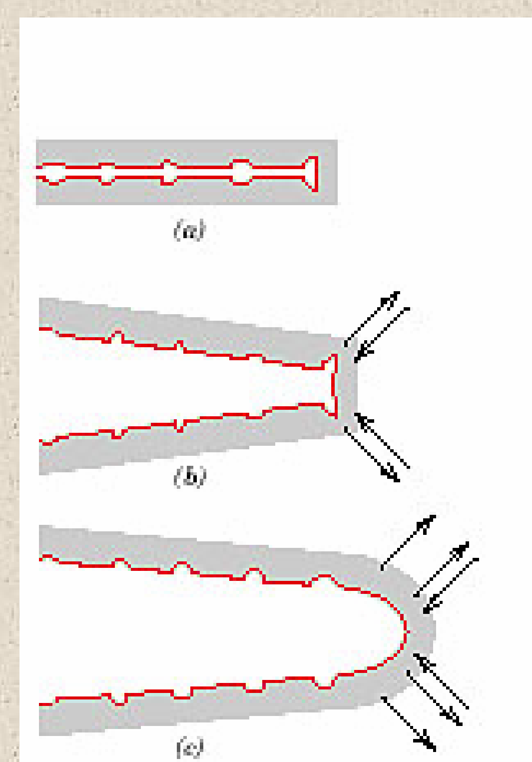
  thermal: $\Downarrow N_f$ by introducing additional stress

  corrosion: $\Downarrow N_f$ by roughening the surface ($\Downarrow N_i$) and increasing crack propagation rates ($\Downarrow N_p$)

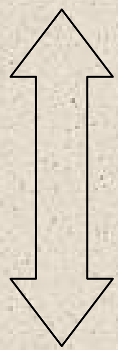
Example

An 8-mm diameter rod is made from a red brass alloy and is subjected to full reversal loading along its axis. If the max tensile and compressive loads are +7500 N and -7500 N respectively, determine the fatigue life.

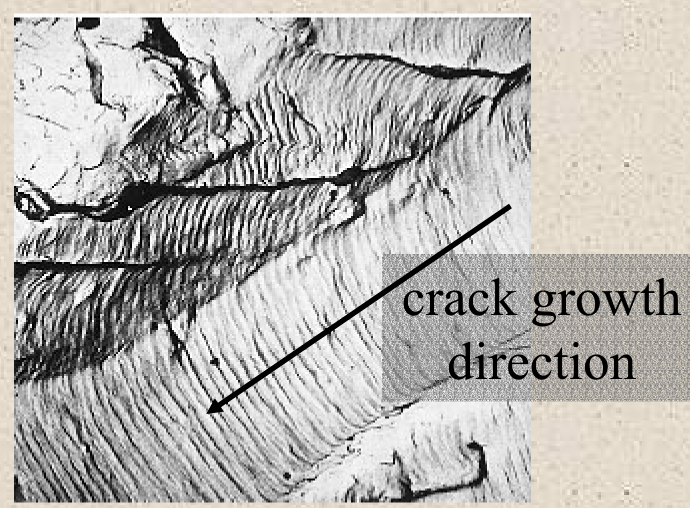
Fatigue crack growth (propagation)



σ_{min}

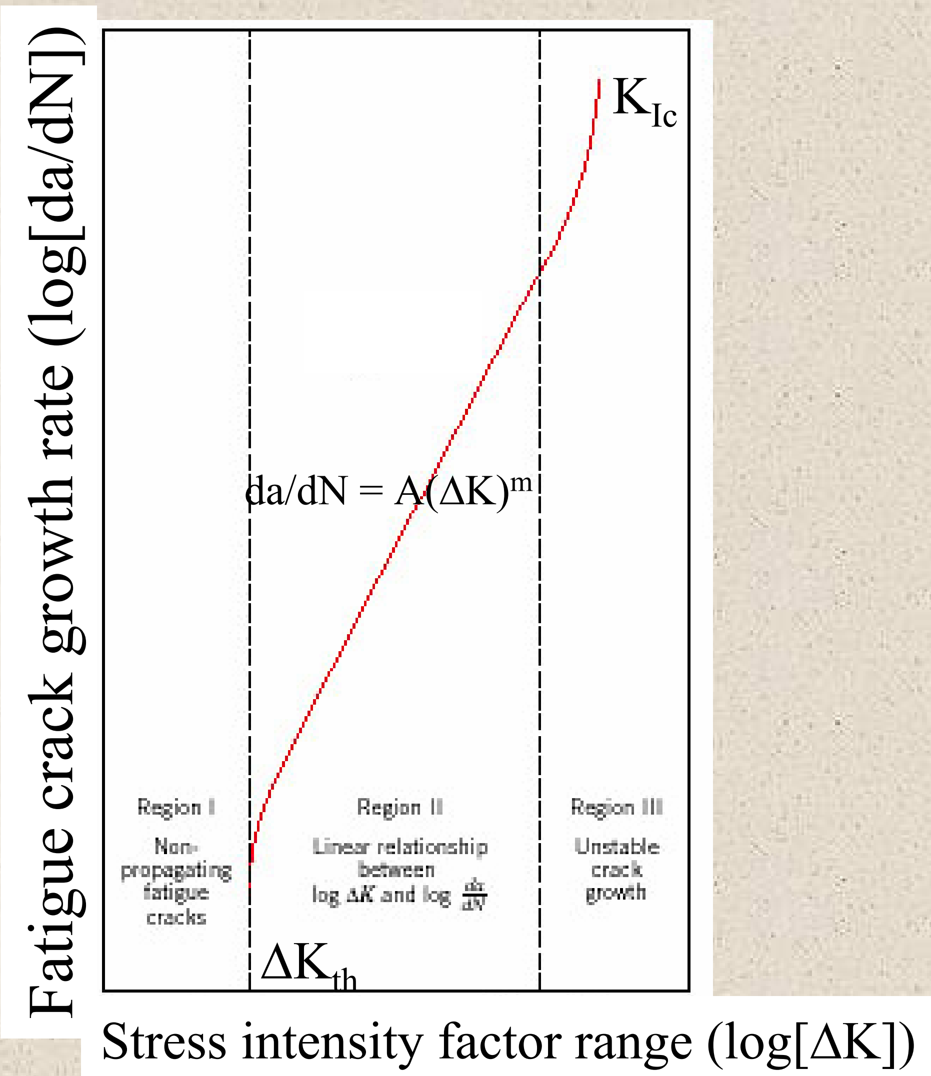


σ_{max}



Fatigue striations

Fatigue crack growth (uses fracture mechanics)



$\Delta K = K_{max} - K_{min}$

$\Delta K = f\,\Delta\sigma\sqrt{\pi a}$

In region II:
$da/dN = A(\Delta K)^m$

$\log(da/dN) = \log A + m \log \Delta K$
which is <u>a straight line with slope m</u>

Lab tests are performed to determine A and m

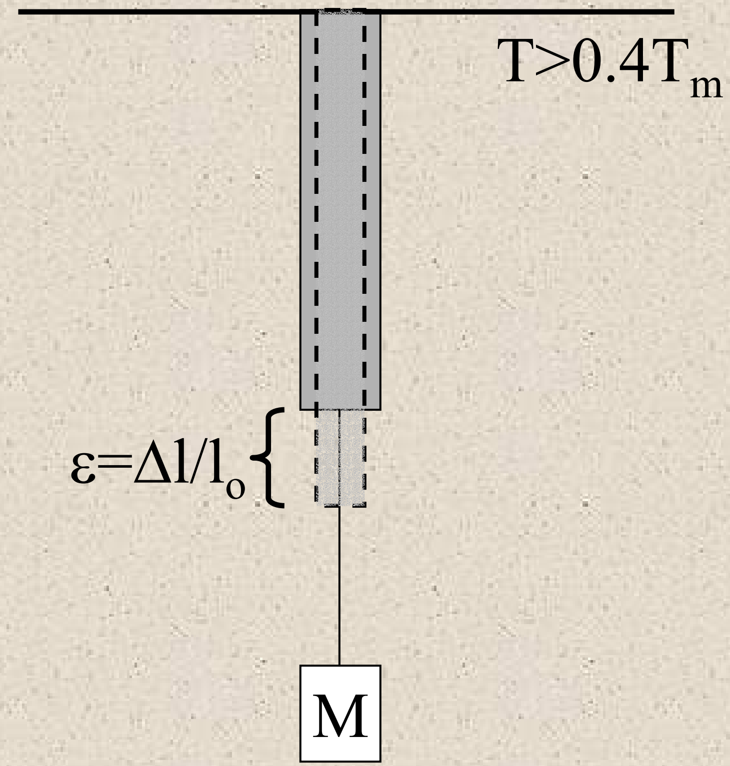
Creep

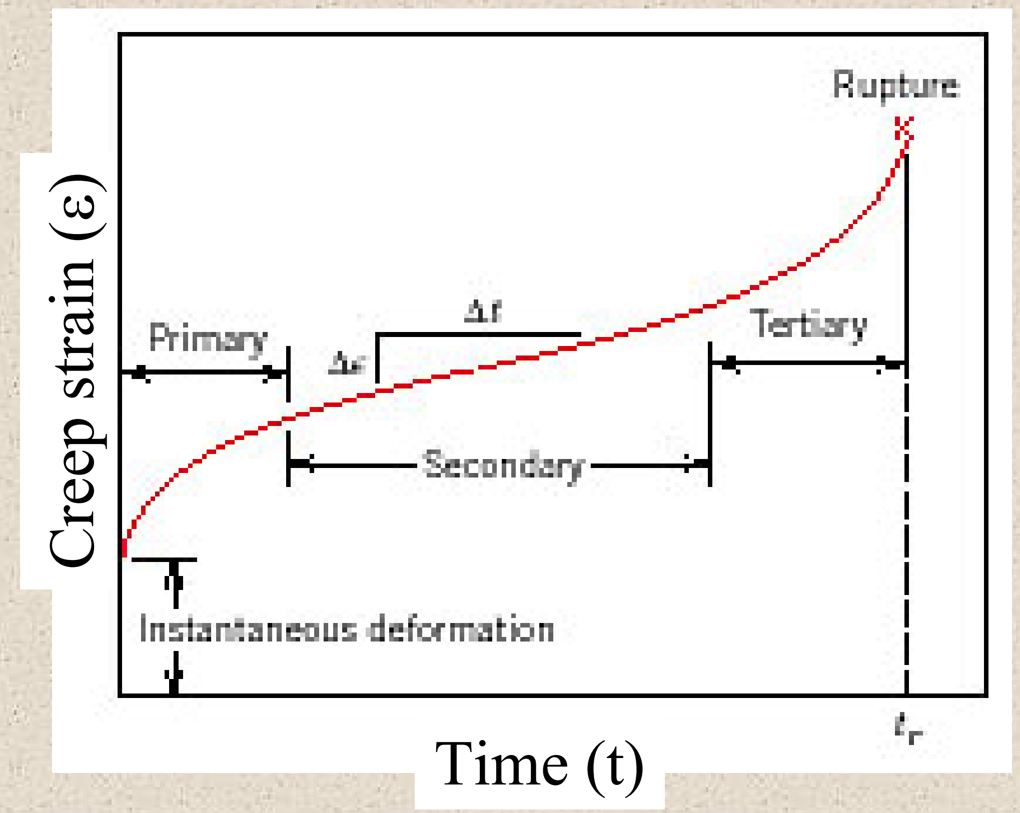
Creep

- Definition: Time dependent, permanent deformation that occurs as a result of stress at elevated temperature.
- Occurs in all material types.
- Becomes significant for metals at temperatures above $0.4T_m$ (T_m in K).
- Caused in part by dislocation climb.
- Determines lifetime for parts such as turbine rotors, steam generators and high pressure steam lines.

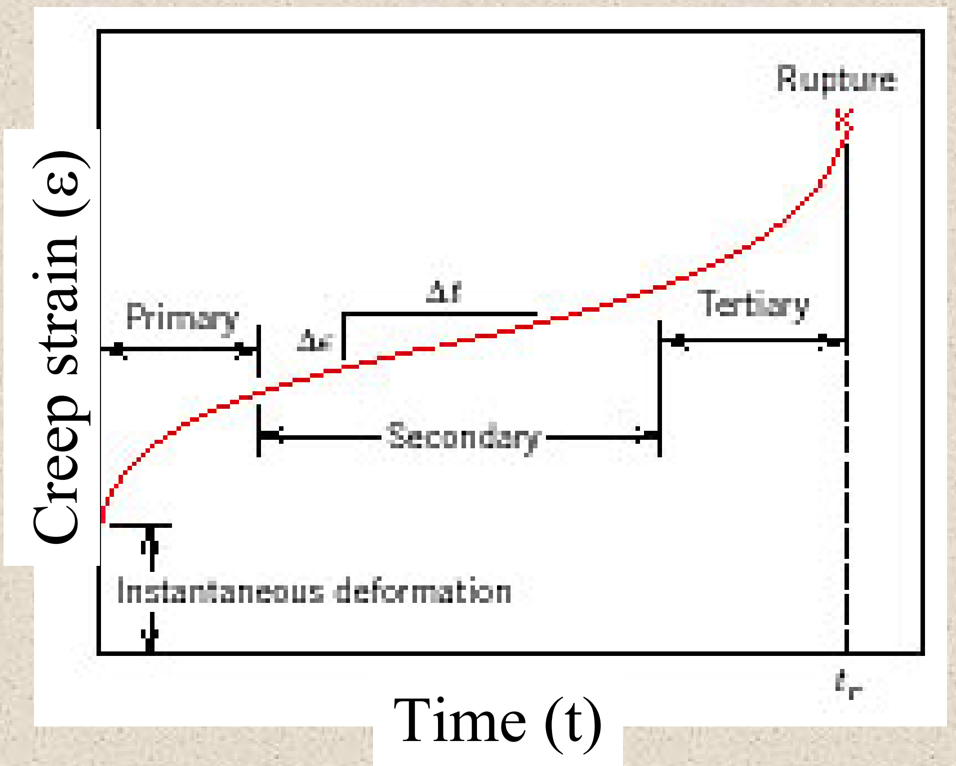
Creep - Phenomenology

Constant load creep test
(creep rupture test)





Creep - Phenomenology



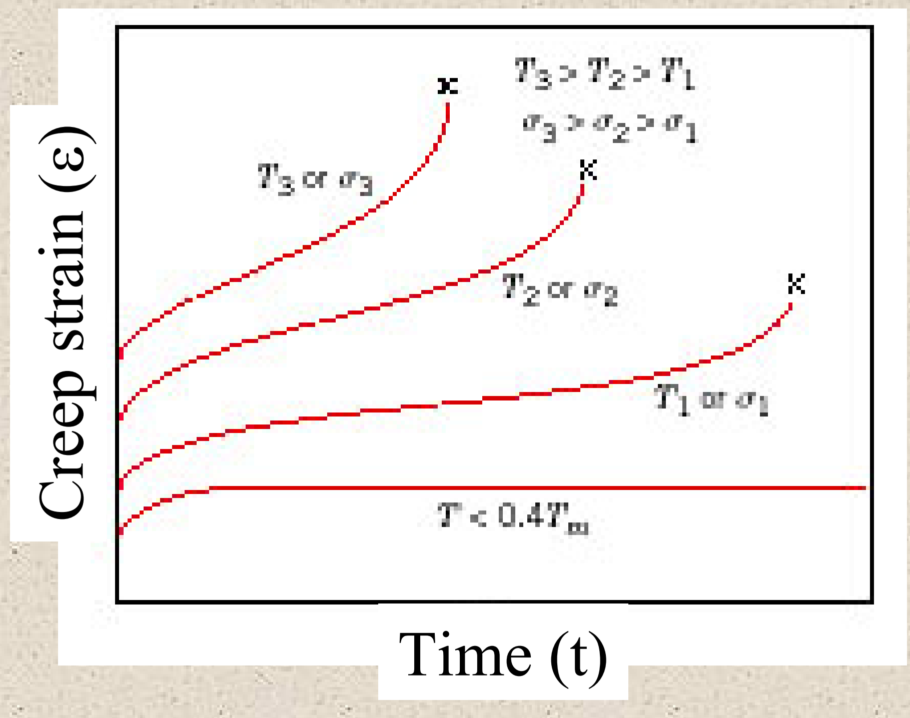
For short term designs the <u>rupture life (t_r)</u> is important to know

For long term designs, the <u>creep rate (Δε/Δt)</u> is important to know

Creep - Effect of Applied Stress and T

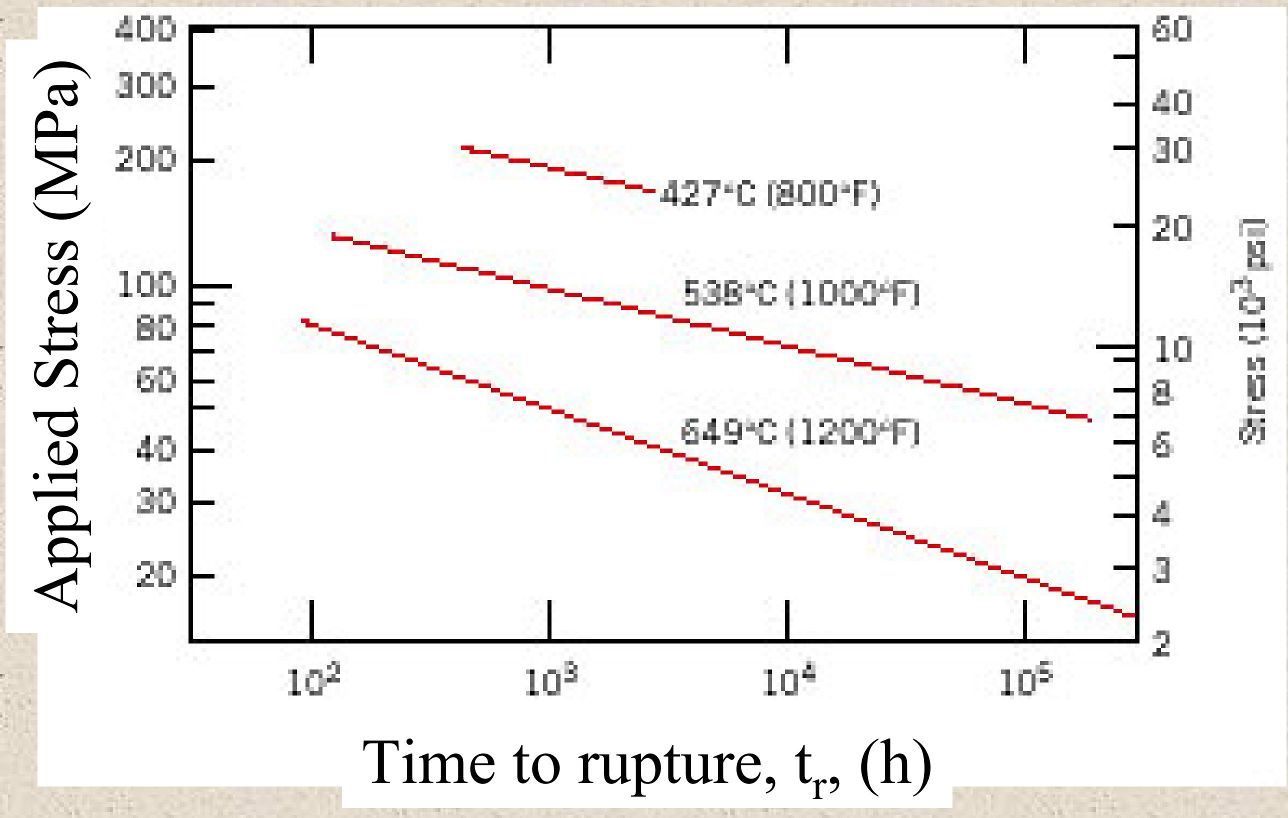
With increasing stress *or* T:

- $\Delta\varepsilon/\Delta t$ increases
- t_r decreases



Effect of Applied Stress and T - short term designs

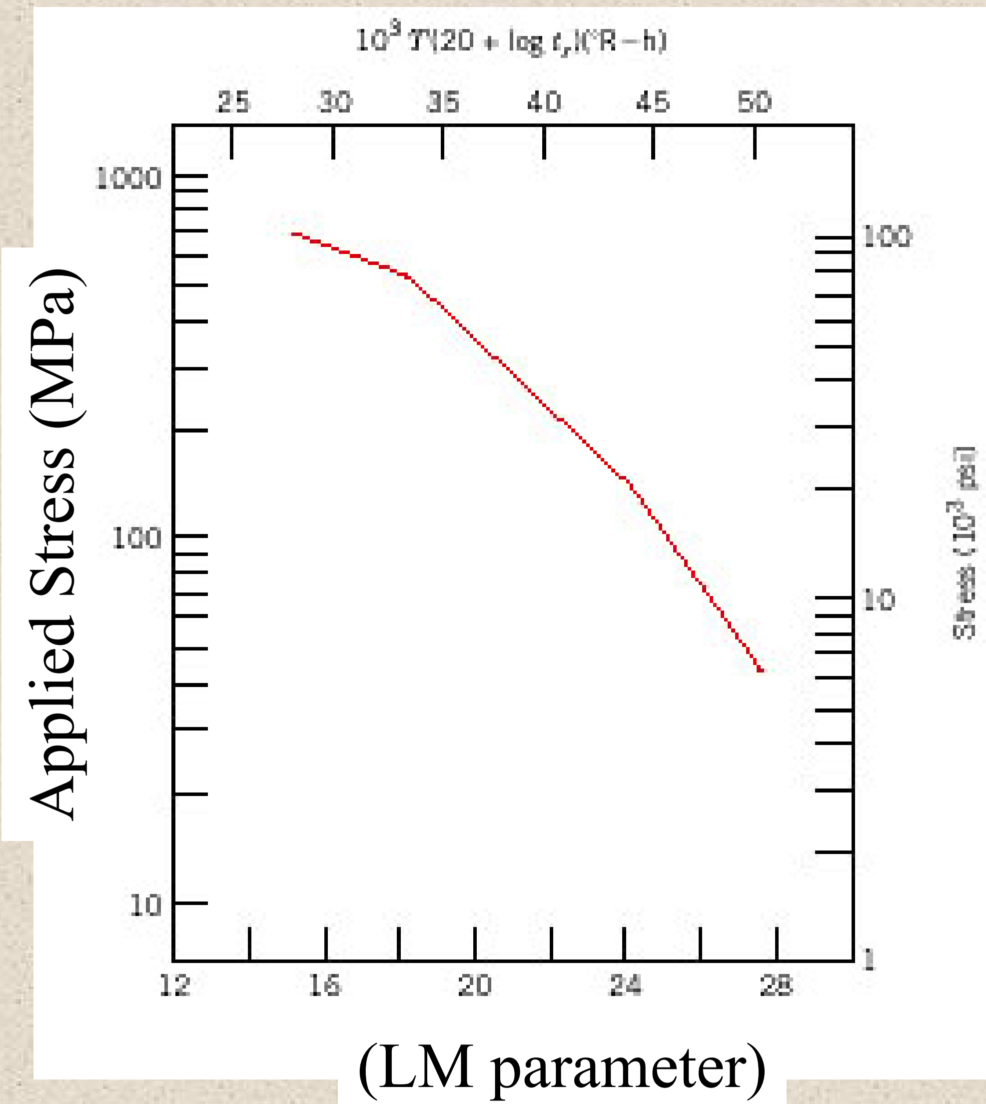
- How creep data is presented for <u>short term design</u>



Larson Miller Parameter - short term designs

- To avoid long test times, creep tests are often performed at temperatures in excess of service temperatures (accelerated testing).
- How do we use extrapolate the high T data down to the service temperatures?
  - Larson-Miller parameter = LM $=T(A + B\ln t)/1000$
  - A, B are constants, T (K), t (hrs)
- At a given applied stress, t varies with T such that the LM parameter remains constant.

Larson Miller parameter - short term designs



- Contains effect of T and applied stress on rupture life

- Know two of three parameters (σ, T or t_r), can determine the third.

Effect of Applied Stress and T - long term design

For long term designs, creep rates are measured.